USE OF A GYRATORY TESTING MACHINE IN EVALUATING BITUMINOUS MIXTURES

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by

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Technical Paper

USE OF A GYRATORY TESTING MACHINE IN EVALUATING BITUMINOUS MIXTURES

TO: K. B. Woods, Director
Joint Highway Research Project

January 7, 1964

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

Project: C-36-6S
File: 2-4-19

Attached is a technical paper entitled "Use of a Gyratory Testing Machine in Evaluating Bituminous Mixtures". This paper has been authored by Mr. Herbert W. Busching, Graduate Assistant, and Professor W. H. Goetz, Research Engineer, on our staff. The paper is a summary of the research conducted by Mr. Busching under the direction of Professor Goetz which was reported to the Board at an earlier date in a final report titled "Stability Relationships of Agratory-Compacted Bituminous Mixtures".

The paper is scheduled for presentation at the Annual Meeting of the Highway Research Board in January 1964. It is presented to the Board for approval of such presentation and possible publication by the HRB.

Respectfully submitted,

Harold L. Michael

Harold L. Michael,
Secretary

HLM:bc

Attachment

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USE OF A GYRATORY TESTING MACHINE
IN EVALUATING BITUMINOUS MIXTURES

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INTRODUCTION

Bituminous mix design methods in current use attempt to relate design to the amount and type of traffic the pavement will be required to withstand (14). Because of the varying and unknown traffic loads to which a bituminous pavement is subjected, design and construction criteria may have to be altered occasionally to provide a realistic correlation between the laboratory design and the in-service traffic conditions. The stability required for pavement at a signalized intersection on a primary truck route may be quite different from that required for a lightly traveled secondary highway. Rutting and shoving of bituminous resurfacing, particularly at signalized intersections (5), indicate that some bituminous mixtures are unstable in certain instances. This instability is sometimes evident even when present design methods predict the mixture should be stable. Evidently design methods in current use are not completely adequate.

It has been found (1, 6) that currently used laboratory compaction methods have not been able to reproduce the in-service density of some bituminous mixtures without producing excessive degradation. Evidence has also been presented which shows that type of compaction is important to the strength that may be expected from a bituminous mixture (1, 2). Researchers (4, 12, 16, 17, 19, 20) in bituminous mixture design methods have indicated a need for reproducing in laboratory test specimens the same properties that the pavement will acquire when used by traffic.

It is recognized that there are disadvantages of prohibitive cost, unknown or uncontrollable variables, etc., which may hinder the useful results of field testing (2[illegible]) and cause gaps to exist between laboratory designs and the in-service traffic condition (8). It has been considered (16) that the horizontal forces due to the movement of the tire might be a main cause of difference between field and laboratory compaction. Also, laboratory procedures which achieve a given density without regard to aggregate orientation or degradation cannot produce representative specimens (1[illegible]).

Some field research has been directed to measuring pavement densification under traffic. It has been found (1[illegible]) that densification of a mix is proportional to the opportunity a mix has to densify. Soils investigations (26) have shown that steel-wheeled rollers produce the greatest density in a zone close to the roller surface. The Hveem design procedure (21) utilizes the kneading compactor in an attempt to reproduce degradation and kneading effects similar to those that might occur under traffic. Schmidt et al. (25) present data to show that for excessive compaction with steel-wheeled rollers pavement density increases with depth from the pavement surface.

Some data (20) have indicated that the gyratory shear method of compaction approximates the in-service pavement condition more closely than other compaction methods. In an attempt to develop improved procedures for the design and control of hot-mix bituminous pavements, the Corps of Engineers at their Waterways Experiment Station, Vicksburg, Mississippi, built a gyratory testing machine based on the

compaction method used by the Texas Highway Department (17, 20, 22). The Corps of Engineers' gyratory testing machine was used extensively in correlatory work with pavements subjected to high tire contact pressures (1, 11). Some experience has also been gained in using a gyratory testing machine for density control of highway bituminous paving projects (9). Because tests have shown that the gyratory testing machine can produce in laboratory specimens density and stability values approaching those that result from heavy aircraft traffic (1), it was decided to attempt to use this machine in the simulation of highway construction and traffic effects on bituminous mixtures.

This study was undertaken to investigate possible applicability of a gyratory compaction and testing machine to the laboratory design of bituminous mixtures for highway uses. In the course of the testing, studies were made of selected laboratory test properties of bituminous mixtures compacted by the gyratory testing machine. To relate the gyratory compaction procedure to a currently used design procedure, comparisons of selected properties of gyratory-compacted specimens were made with similar properties of kneading-compacted specimens. Because mixture stability was considered one of the most important properties desired in a bituminous mixture, all machine variables investigated in the study were evaluated by their effect on stability. The Hveem stabilometer was used to obtain a measure of specimen stability.

EQUIPMENT AND TESTING METHOD

With the exception of the gyratory testing machine, all equipment used in this study for the compaction and testing of bituminous mixtures is standardized equipment found in many bituminous mixture design laboratories. The gyratory testing machine, shown in Figures 1 and 2, is a mechanized compaction and testing apparatus similar in principle to the manually-operated Texas compaction apparatus. Compaction of a specimen occurs when the machine exerts a combined kneading and shearing action on a specimen contained in a steel mold. Vertical pressures are maintained against the specimen by hydraulically-controlled steel rams whose faces are parallel to one another. The chuck holding the steel mold is mechanized so that it can move as two rollers, one on each side of the chuck flange, revolve. The lower roller is adjustable and permits the chuck flange to be rotated or pitched about its vertical axis.

Different degrees of gyratory action may be obtained by employing the fixed, air-filled, or oil-filled upper rollers shown in Figure 2. Most of the compaction in this study was accomplished using a fixed upper roller. The machine as operated with this roller produced gyratory action of the fixed-deformation type. A smaller number of tests were performed on specimens compacted by the machine using the air-filled upper roller. The air-filled upper roller permitted a fixed-stress, variable-deformation gyratory action.

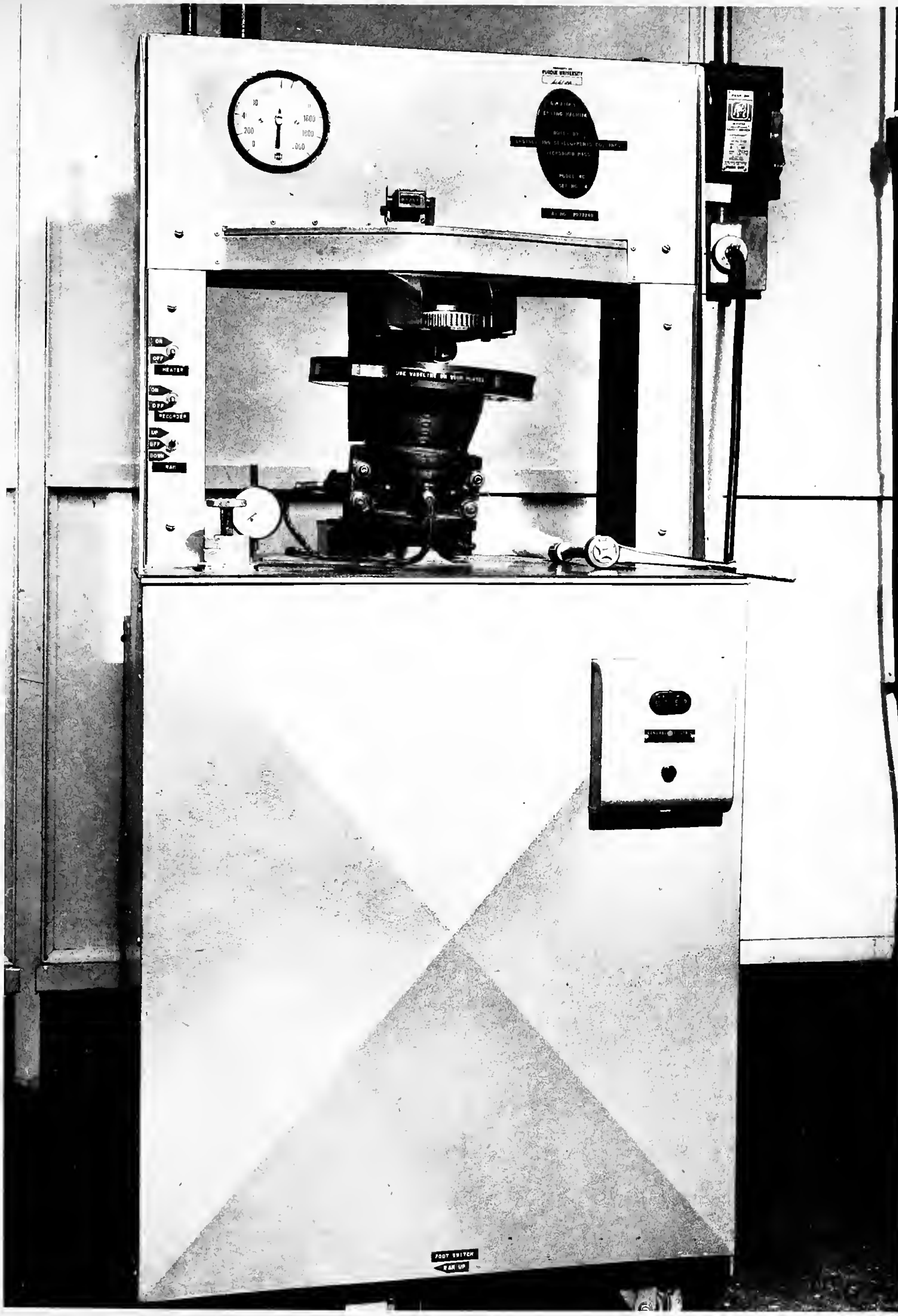

FIG. 1 GYRATORY TESTING MACHINE

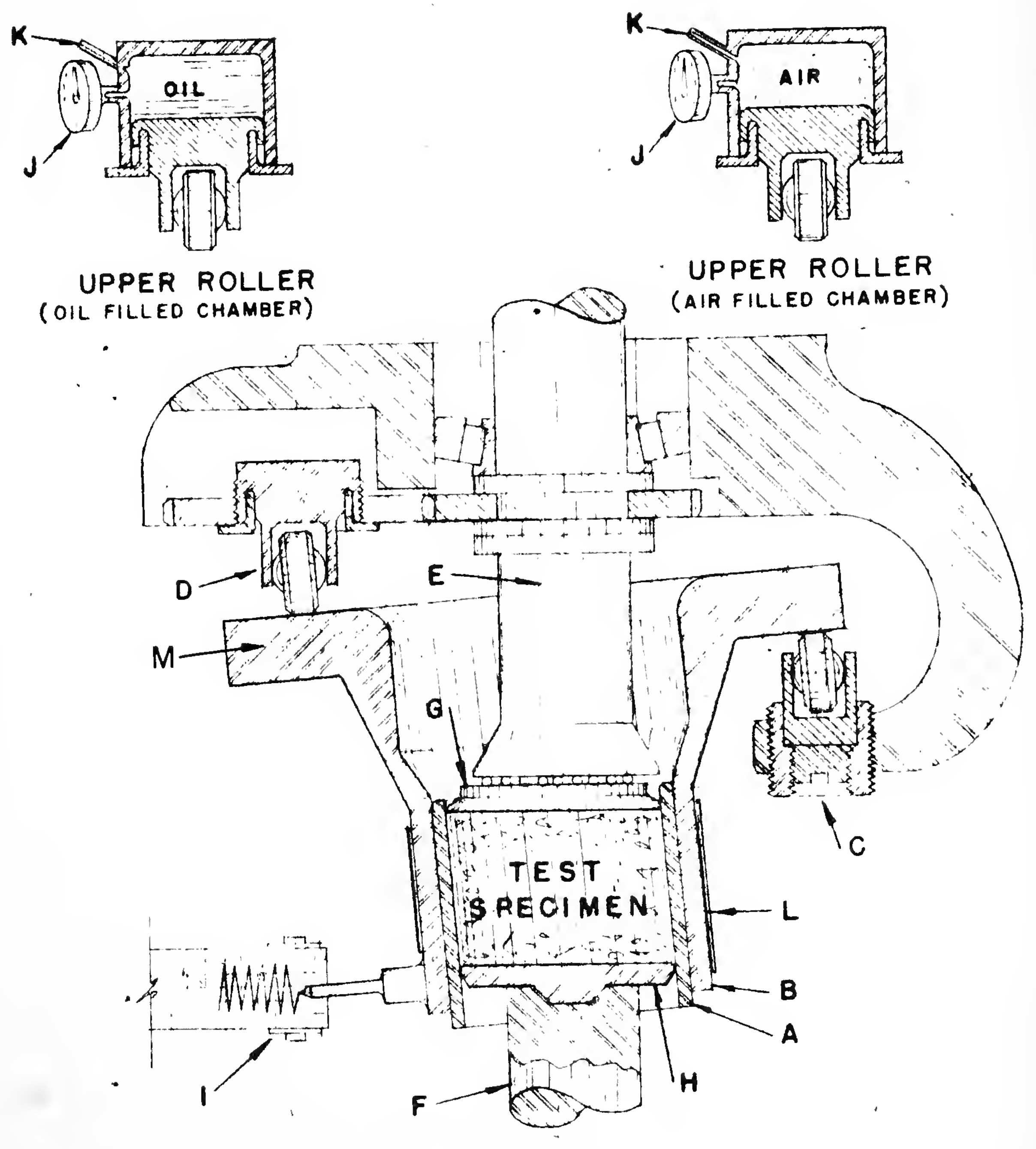

FIG. 2 SCHEMATIC SIDE VIEW OF SECTION THROUGH GYRATING MECHANISM
(AFTER CORPS OF ENGINEERS)

Key to Details of Figure 2

A. Specimen Mold

B. Mold Chuck

C. Lower Roller

D. Upper Roller

E. Upper Ram Shaft

F. Lower Ram Shaft

G. Upper Head

H. Lower Head

I. Gyrograph

J. Pressure Gage

K. Filling Valve

L. Heating Element

M. Chuck Flange

Although the pitch of the flange on a line connecting the rollers (which act as point loads 180° apart) is fixed, the flange can rotate about the line between these two points, and by rotation about this line the mold chuck can develop gyratory angles in excess of the angle made by the line between the rollers. Changes in the gyratory angle reflect the plastic properties of the material in the mold and are recorded on a gyrograph by a mechanical pen recorder. The more plastic and the weaker the specimen, the larger will be the gyratory angle and the wider will be the gyrograph.

The gyratory testing machine used in this study produced a compacted specimen whose dimensions were compatible for stability testing by several currently used design procedures (14). The Hveem stabilometer was selected as the basis for stability evaluation of compacted specimens because Hveem stability values have had good correlation with field performance of bituminous mixtures. Hveem and Davis (7) believe that materials with varying stabilities would not undergo any marked difference in relative classification whether tested in the stabilometer or in a triaxial device where a theoretical stress analysis is possible. The stabilometer test is relatively fast and easy to perform and hence applicable to test [illegible] a large number of specimens in a short time. Numerous references describe the Hveem stabilometer and method of test (3, 14, 21).

MATERIALS

The bituminous mixtures used for this study were selected in relation to those currently used by the Indiana State Highway Commission for their type B surface. It was thought that the gradation of the mixtures selected would make them applicable to testing in both the gyratory machine and the Hveem stabilometer without special modification of standard test procedures.

The types of aggregates used were crushed limestone, dune sand, natural sand and limestone filler. Aggregate materials were tested for specific gravity and absorption according to ASTM methods C 127 and C 128. The results of these tests are shown in Table 1. The commercially produced and washed aggregates, after being brought to the laboratory, were sieved into the required sizes and then washed again before storage prior to blending.

The two gradations used in this study are shown in Figure 3. The sieve size fractions of the aggregates used corresponded to the sizes specified by the Indiana State Highway Commission for Hot Asphaltic Concrete Surface - Type B. The Fuller's maximum density gradation for a gradation utilizing a one-half inch maximum sieve size was calculated from the Fuller and Thompson empirical formula:

$$P_i = P_o(D_i/D_o)^{\frac{1}{2}}$$

where: P_i = percent smaller than D_i

P_o = percent smaller than D_o

D_o = maximum sieve size in gradation

D_i = intermediate sieve size in gradation

Table 1

Results of Tests on Aggregates

Size	Material	Bulk Specific Gravity	Apparent Specific Gravity	% Absorption
1/2"-3/8"	Limestone	2.63	2.68	1.10
3/8"-#4	Limestone	2.67	2.71	0.90
#4-#6	Limestone	2.63	2.71	1.74
#6-#8	Limestone	2.62	2.70	1.94
#8-#16	Natural Sand	2.59	2.72	2.77
#16-#50	Natural Sand	2.60	2.70	2.45
#50-#100	Natural Sand	2.63	2.70	2.63
#100-#200	Dune Sand	2.59	2.65	1.27
Passing #200	Limestone	2.71	--	--

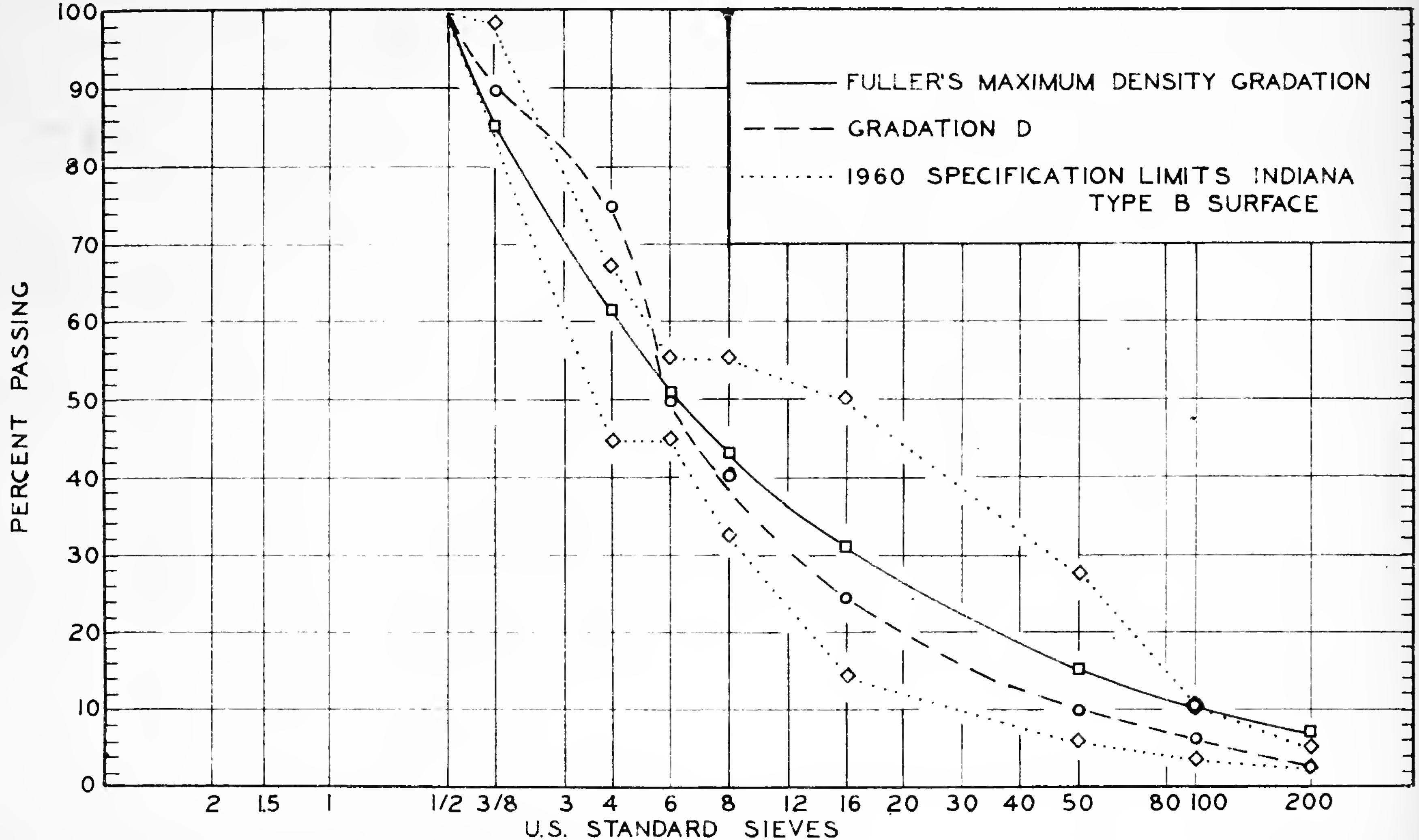

FIG. 3 AGGREGATE GRADATION CURVES

Table 2

Results of Tests on Asphalt Cement

Specific Gravity @ 77°F	[illegible]
Softening Point, Ring and Ball, °F	[illegible]
Ductility at 77°F, 5 cm/min, cm.	200 +
Penetration, 100 grams, 5 sec. 77°F	[illegible]
Penetration, 200 grams, 60 sec., 39°F	[illegible]
Loss on Heating, 50 grams, 5 hr., 325°F, percent	[illegible]
Penetration of Residue, percent of original	[illegible]
Flash Point, Cleveland Open Cup, °F	595
Solubility of CCl_4, percent	[illegible]

Gradation D material was similar to Type B surface specified by the 1960 Indiana State Highway Commission specifications (10).

A 60-70 penetration grade asphalt was used in this study. This is the penetration grade currently used by the State of Indiana for hot asphaltic concrete. Results of tests on this asphalt are presented in Table 2.

PROCEDURE

Aggregates separated into component sieve-size fractions were batched according to the blend formula. Aggregate batches of 1100 grams each were used throughout the study and batching was accomplished with cold dried aggregates using a scale sensitive to one gram. Prior to mixing, aggregate batches and asphalt were heated separately to 325±5F. Mixing bowl, paddle, and other utensils were also heated to 325±5F to minimize heat loss during mixing. Asphalt content for the entire study was specified as percent by weight of the aggregate. The constituents of each batch were mixed in a modified Hobart mixer for two minutes and then transferred to curing pans and cured for a fifteen hour period at 140±5F in a Hotpack oven provided with forced draft air circulation. After the curing period each batch was reheated to 225±5F for compaction.

Two types of compaction were used in this study: kneading compaction and gyratory compaction. Kneading compaction was performed with the California kneading compactor using the compaction procedure outlined by the Asphalt Institute (14).

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The sequence of compaction in the gyratory testing machine was chosen to attempt to simulate compaction that might be expected from construction equipment and traffic. Accordingly, compaction in the gyratory testing machine was divided into two phases -- initial compaction and secondary compaction. Initial compaction was carried out in all cases with the fixed upper roller and a specimen temperature of 225±5F. Either 10 or 20 initial compaction revolutions were imposed on the specimen in an attempt to bracket the range of compaction a bituminous layer might receive from construction compaction equipment. Ram pressures of 50, 100, and 150 psi were utilized.

Secondary compaction was imposed on specimens which had undergone initial compaction. Secondary compaction involved 30, 60, 90, or 400 additional revolutions at secondary pressures of 50, 100, or 150 psi and a temperature of 140F. The range of ram pressures - 50 to 150 psi - was selected in an attempt to simulate normally severe tire contact pressures that might be imposed on the bituminous mixture by traffic.

After completion of compaction in either the gyratory testing machine or the California kneading compactor, specimens were tested in the Hveem stabilometer. The complete procedure used in the study for testing compacted bituminous specimens in the Hveem stabilometer is described in reference (14).

Bulk specific gravity determinations were made for all compacted specimens after stabilometer testing. Rice specific gravity was obtained for those specimens for which percent voids were to be computed. The Rice specific gravity procedure is detailed in ASTM Special Technical Publication No. 191 (23).

Uniformity of unit weight with specimen height was studied by cutting the compacted specimens in half with a masonry saw. Because the sawing operation wetted the specimen halves, they were washed free of dust and placed in water for a 24-hr absorption period. [illegible] the submerged and saturated, surface-dry specimen weights were [illegible] the specimen halves were placed on absorbent paper and air-dried at room temperature with the air of a fan for 24 hours. The weight in air was then recorded and specific gravity determinations were made.

RESULTS

In this section test results are presented together with discussion and evaluation. For clarity of presentation graphical illustrations of trends indicated by data are used whenever possible. The following topics are considered in this section:

Influence of stabilometer test on compacted specimens

Fixed-roller operation

Initial compaction

Secondary compaction

Gradation

Design procedures

Design of dense-graded mixes

Design for open-graded mixes

Variation of unit weight with specimen height

Particle orientation

Influence of Stabilometer Test on Compacted Specimens

It was recognized that specimens tested in the Hveem stabilometer were deformed in the course of testing. To evaluate whether or not this deformation had a measurable affect on the unit weight of compacted specimens, ten specimens were compacted in the gyratory testing machine using a 100 psi ram pressure, 10 revolutions, and a 1° angle of gyration. Bulk unit weights of these specimens were determined both after compaction and after testing in the stabilometer. A statistical test showed that the stabilometer test caused a significant increase in bulk unit weight of these specimens. Table 9 shows bulk unit weights determined before and after the stabilometer test.

Fixed-Roller Operation

The major portions of this study involved stability measurement of specimens compacted using fixed-roller operation in the gyratory testing machine. To investigate the variation in stability caused by the factors involved in the gyratory compaction process an analysis of variance test was used. Variables for this series of tests included the following:

Factor	Levels of Factor
Secondary pressure, psi	0, 50, 100, 150
Secondary revolutions	30, 60, 90
Initial pressure, psi	50, 100, 150

Table 3

Comparison of Bulk Unit Weight Before and After Stabilometer Test

(1) Bulk Unit Weight - pcf Before Stabilometer Test	(2) After Stabilometer Test	Bulk Unit Weight - pcf (2) - (1)
142.0	144.1	2.1
141.6	143.5	2.1
141.0	142.9	1.9
141.0	142.9	1.9
142.9	144.1	1.2
143.5	144.8	1.3
141.6	143.5	1.9
143.5	144.8	1.3
141.6	142.9	1.3
141.0	142.9	1.9
		16.7

$$\text{Mean difference} = \frac{16.7}{10} = 1.67 \text{ pcf}$$

Pressures were chosen to be representative of the range of contact pressures that might be expected from construction equipment and traffic. The initial number of revolutions (10 or 20) was chosen to bracket the range of compaction a bituminous layer might receive from construction compaction equipment

Two gradations - one dense and one open - were used to study effects of aggregate gradation on specimen stability.

The sequence of compaction involved simulated construction compaction at either 10 or 20 initial revolutions and 50, 100, or 150 psi initial pressure. This initial compaction was carried out at 225F and utilized fixed-roller operation and a 1° angle of gyration in all tests. Simulated traffic or secondary compaction involved additional revolutions (30, 60, or 90) and secondary pressures of 50, 100, or 150 psi. Secondary compaction was carried out at 140F. Subsequent to secondary compaction, specimens were tested in the Hveem stabilometer. For the first series of tests, asphalt content was not varied. One hundred ninety-two specimens containing four percent asphalt were used for this series of tests.

Four three-way analysis of variance tests were required to analyze data common to each of two gradations and two values of initial revolutions. A ranking of the relative importance of the three factors in effecting changes in stability can be obtained from the size of the mean squares shown in the last columns of Tables 4, 5, 6, and 7. Generally it may be said that for the increments chosen, the factors

Table 4

Analysis of Variance (Fixed Effects Model)

Fuller's Maximum Density Gradation
10 Revolution Initial Compaction

Factors	Levels of Factor
A = Secondary Revolutions	3
B = Secondary Pressure	4
C = Initial Pressure	3

H_o: Stability not affected by Factor (α = 0.05).

Factor	Degrees of Freedom	Sum of Squares	Mean Squares	Variance Ratio	$F_{0.05}$	Decision
A	2	58.39	29.20	7.19	3.89	Reject H_o
B	3	1198.76	399.59	98.42	3.49	Reject H_o
C	2	132.03	66.02	16.26	3.89	Reject H_o
AB	6	10.18	1.70	0.42	3.00	Accept H_o
AC	4	19.24	4.81	1.18	3.26	Accept H_o
BC	6	94.84	15.81	3.89	3.00	Reject H_o
ABC	12	48.74	4.06			

Table 5

Analysis of Variance (Fixed Effects Model)

Fuller's Maximum Density Gradation
20 Revolution Initial Compaction

Factors	Levels of Factor
A - Secondary Revolutions	3
B - Secondary Pressure	4
C - Initial Pressure	3

H_o: Stability not affected by Factor ($\alpha = 0.05$).

Factor	Degrees of Freedom	Sum of Squares	Mean Squares	Variance Ratio	$F_{0.05}$	Decision
A	2	75.95	37.98	15.76	3.89	Reject H_o
B	3	1197.34	399.11	165.61	3.49	Reject H_o
C	2	222.19	111.10	46.10	3.89	Reject H_o
AB	6	21.14	3.52	1.46	3.00	Accept H_o
AC	4	8.93	2.23	0.95	3.26	Accept H_o
BC	6	91.64	15.27	6.34	3.00	Reject H_o
ABC	12	28.95	2.41			

Table 6

Analysis of Variance (Fixed Effects Model)

Gradation D
10 Revolution Initial Compaction

Factors	Levels of Factor
A - Secondary Revolutions	3
B - Secondary Pressure	4
C - Initial Pressure	3

H_o: Stability not affected by Factor (α = 0.05).

Factor	Degrees of Freedom	Sum of Squares	Mean Squares	Variance Ratio	$F_{0.05}$	Decision
A	2	193.54	96.77	76.2[illegible]	[illegible]	Reject H_o
B	3	1379.2[illegible]	[illegible]	[illegible]	[illegible]	Reject H_o
C	2	160.97	80.49	[illegible]	[illegible]	Reject H_o
AB	6	74.77	12.46	[illegible]	[illegible]	Reject H_o
AC	4	[illegible].79	[illegible]	[illegible]	[illegible]	[illegible]
BC	6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ABC	[illegible]	[illegible]	[illegible]			

Table 7

Analysis of Variance (Fixed Effects Model)

Gradation D
20 Revolution Initial Compaction

Factors	Levels of Factor
A - Secondary Revolutions	3
B - Secondary Pressure	4
C - Initial Pressure	3

H_o: Stability not affected by Factor (α = 0.05).

Factor	Degrees of Freedom	Sum of Squares	Mean Squares	Variance Ratio	$F_{.05}$	Decision
A	2	180.95	90.48	127.44	3.89	Reject H_o
B	3	1424.0[illegible]	474.68	668.[illegible]	3.49	Reject H_o
C	2	310.16	155.08	218.4[illegible]	3.89	Reject H_o
AB	6	45.08	7.51	10.5[illegible]	3.00	Reject H_o
AC	4	1.[illegible]	0.37	[illegible]	3.26	Accept H_o
BC	6	19.0[illegible]	3.[illegible]	4.46	3.00	Reject H_o
ABC	12	[illegible]	[illegible]			

most important in increasing stability values were, in order of importance: secondary pressure, initial pressure, and secondary revolutions.

A five-way analysis of variance test (15) was used to evaluate the effect of all five variable factors on specimen stability. This analysis included the following factors and levels of factors:

Factor	Levels of Factor
A - Secondary revolutions	30, 60, 90, 400
B - Secondary pressure, psi	0, 50, 100, 150
C - Initial pressure, psi	50, 100, 150
D - Initial revolutions	10, 20
E - Gradation	Fuller's maximum density and gradation D

This second analysis differed from the three-way analysis of variance in that it included factors of initial revolutions and gradations as well as another level of secondary revolutions. Results of this analysis of variance are presented in Table 8. A quantitative estimate of the importance of each factor may be obtained from the relative sizes of the numbers listed in the column headed "Estimate of σ^2 Factor". For the five-way analysis of variance, the factors most significant in changing specimen stability were, in order of importance: secondary revolutions, initial pressure, secondary pressure, initial revolutions, and gradation.

Table 8

Analysis of Variance (Fixed Effects Model)
5-Way Classification

H_o: Stability not affected by factor ($\alpha = 0.05$).

Factors	Mean Sum of Squares	Degrees of Freedom	F	$F_{60, .05}$	Decision	Estimate of σ^2 Factor
A - Secondary Revolutions	387.8	3	129.3	2.76	Reject H_o	8.0
B - Secondary Pressures	279.2	3	93.1	2.76	Reject H_o	5.7
C - Initial Pressures	475.8	2	237.9	3.15	Reject H_o	7.4
D - Initial Revolutions	324.7	1	234.7	4.00	Reject H_o	2.4
E - Gradations	80.2	1	80.2	4.00	Reject H_o	0.8

The ranking of factors in the 5-way analysis of variance differed from the 3-factor ranking most noticeably in the reversal of the importance of secondary pressure and secondary revolutions. This was due to the large (400) secondary revolutions value added to the levels of this factor. A controlled field study would be necessary to determine how closely field compaction was simulated by the sequences of laboratory compaction.

It should be noted that the analysis of variance technique used here is a general method that may be used for investigating the effects of any number of variables on specimen properties. The estimate of σ^2 factor shown in the last column of Table 8 may be replaced in a more comprehensive study by estimates of regression for each factor. In this way linear, quadratic, and higher order effects of each factor could be measured. These effects could be obtained from a computer analysis which would be necessary for large-scale correlation between laboratory and field results.

Initial Compaction

The effect of initial compaction pressure on initial stability of specimens is shown in the plot of Hveem stability vs initial pressure in Figure 4. For this portion of the study a constant asphalt content of four percent was used. In all cases increasing the initial compaction pressure increased initial stability. Generally the increase in pressure from 100 psi to 150 psi increased stability more than the increase in

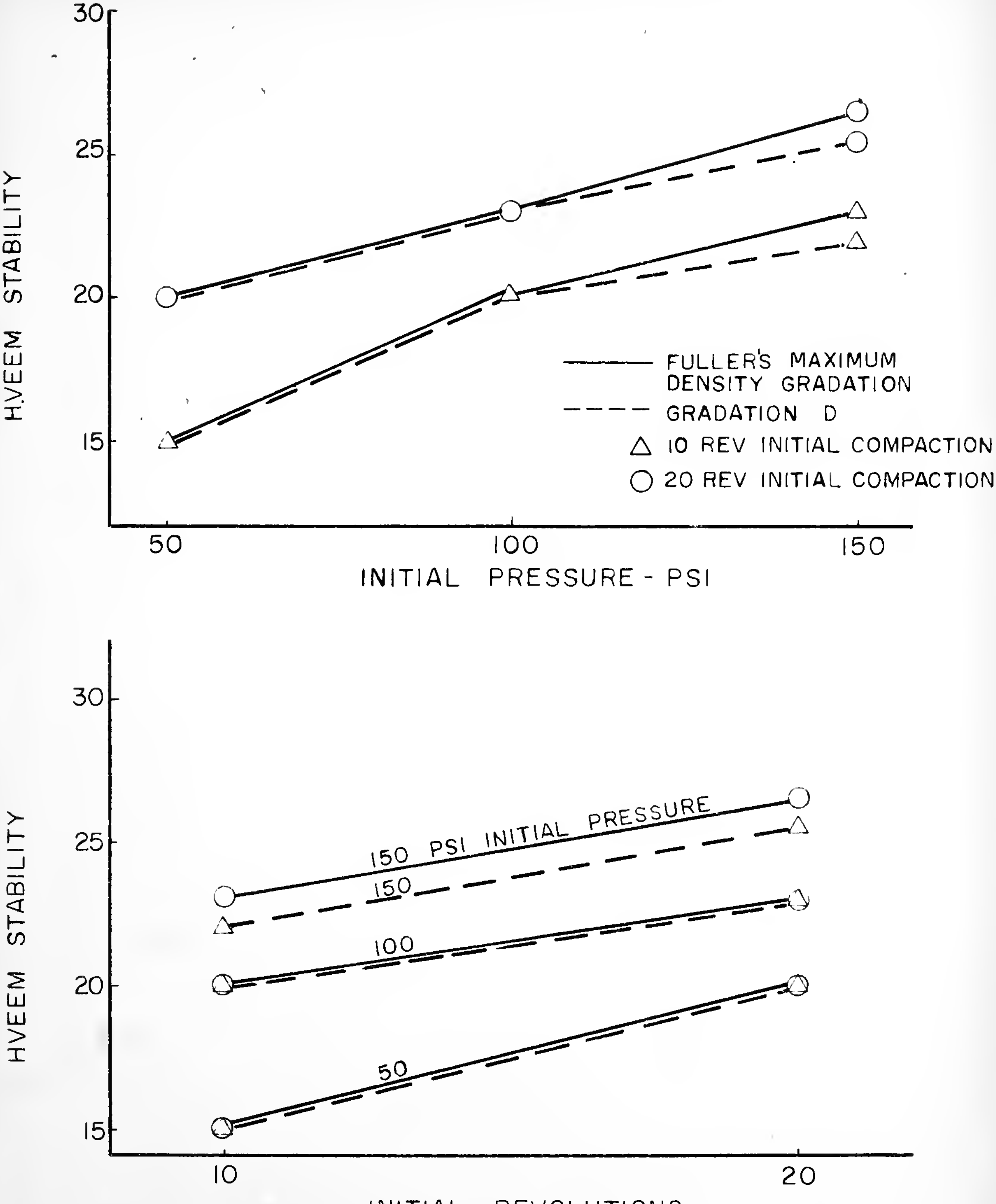

FIG. 4 EFFECTS OF INITIAL PRESSURE AND INITIAL REVOLUTIONS ON SPECIMEN STABILITY

pressure from 50 psi to 100 psi. Each point in Figure 4 represents the average of three stability values that differed from one another by less than one and one-half stability units.

From the plot of Hveem stability vs initial revolutions shown in the lower half of Figure 4 it is seen that increasing initial revolutions from 10 to 20 increased initial stability in all cases. From the slopes of the lines it is seen that the increase in initial revolutions is most effective in increasing initial stability of specimens compacted at low pressure.

It should be noted that the confinement and deformation characteristics in the gyratory testing machine operating with fixed-roller conditions are different from those encountered in which deformation progresses. Under compaction equipment in the field, the layer of bituminous material will become more dense. Accompanying this densification there will be an increase in bearing capacity and lateral support so that subsequent passes with compacting equipment will cause successively smaller deformations. Compaction using the fixed-roller operation deforms the specimen by an angular amount at least equal to the gyratory angle (in this case 1°). Since this movement is greater than that produced by roller or traffic coverages, except perhaps for the first few roller passes, the progression of density and stability in the bituminous specimens is more rapid than is the case for the pavement.

Secondary Compaction

Figures 5, 6, and 7 may be interpreted as indications of rutting potential due to compaction under varying secondary compaction for mixtures compacted initially for 20 revolutions at 1° angle using 50, 100 and 150 psi initial pressures. The semilog plots of axial deformation vs number of revolutions record axial deformation as the difference between specimen height when only a static load was applied and speciman height after some number of revolutions. From these figures it will be noted that the curves are concave downward only for secondary compaction pressures equal to or greater than the initial compaction pressure. Rate of axial deformation decreases during secondary compaction if initial compaction pressure exceeds secondary compaction pressure. It would seem from these comparisons that high tire contact pressures might contribute considerably to densification in cases where initial compaction did not sufficiently densify the mix. In all cases observed in Figures 5 to 7, axial deformation increased. This indicates that specimen confinement in the compaction mold was sufficient to prevent particle orientation that would have resulted in a decrease in unit weight.

The number of secondary revolutions was varied in an attempt to simulate traffic coverages and to obtain an estimate of the variation of specimen stability with time under traffic. Figures 8, 9, 10, and 11 present semilog plots of Hveem stability vs number of revolutions for all 192 specimens compacted using fixed-roller operation. The solid black symbols in each figure represent the values of initial

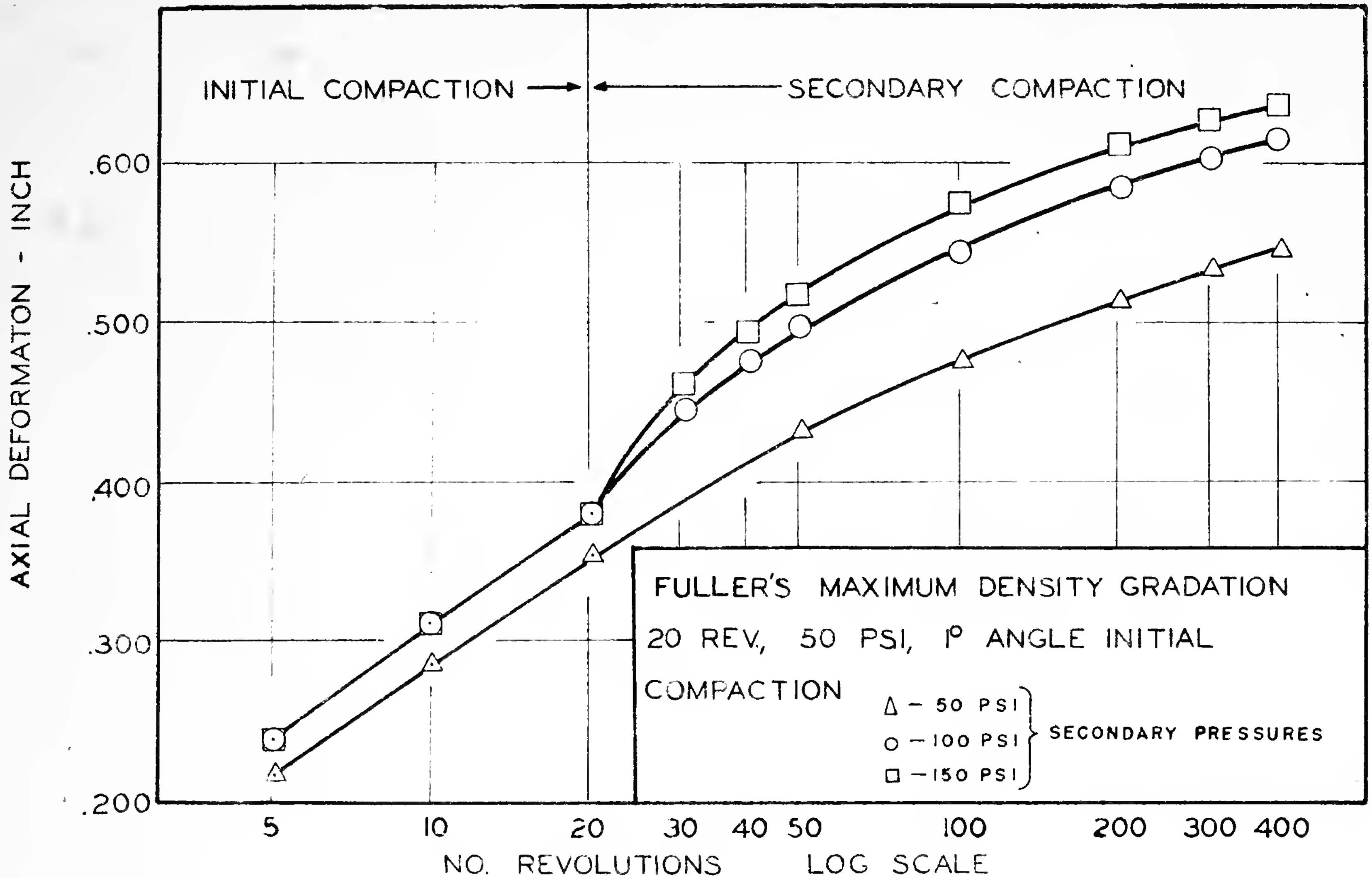

FIG. 5 AXIAL DEFORMATION VS NO. REVOLUTIONS

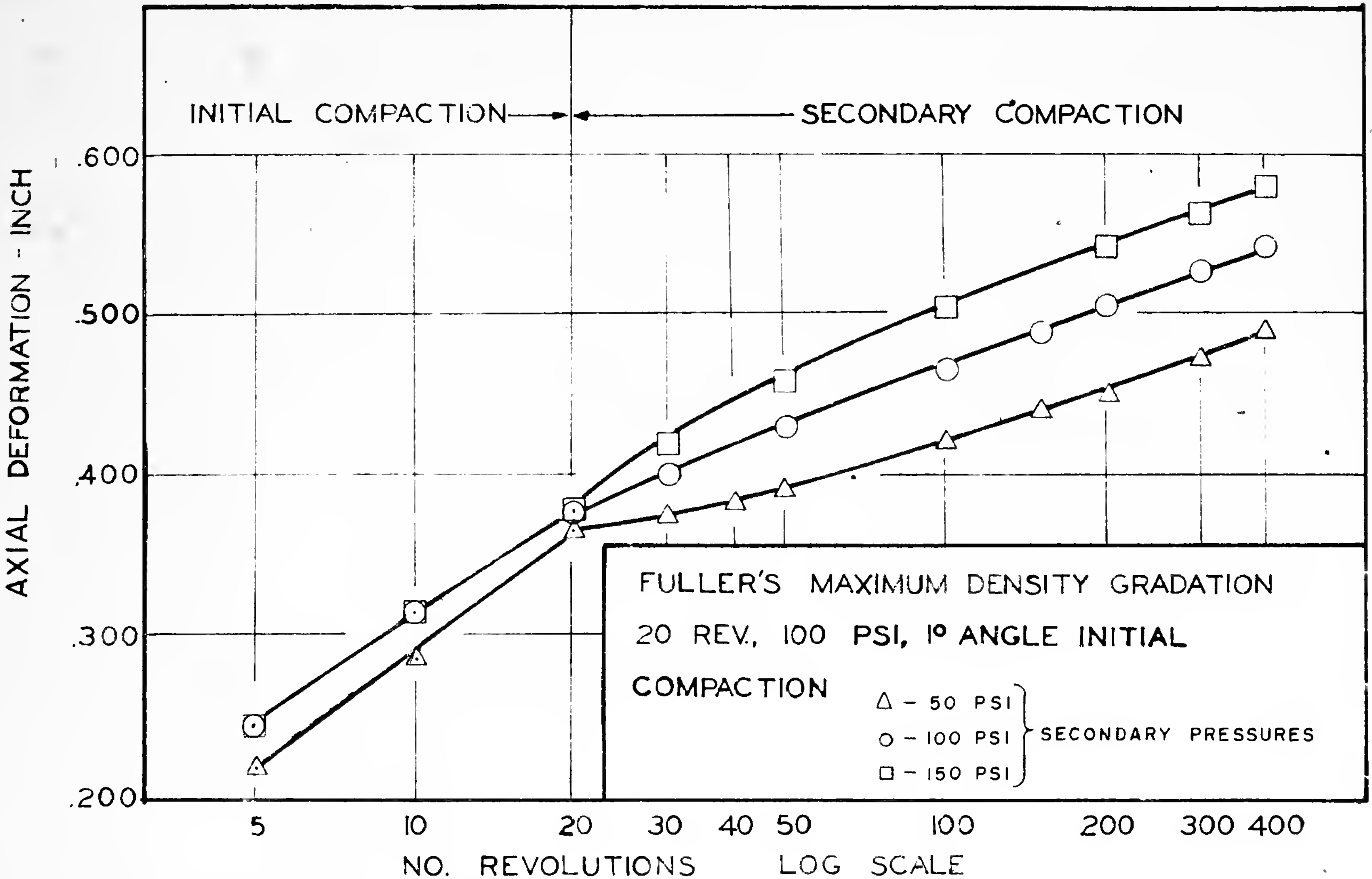

FIG. 6 AXIAL DEFORMATION VS NO. REVOLUTIONS

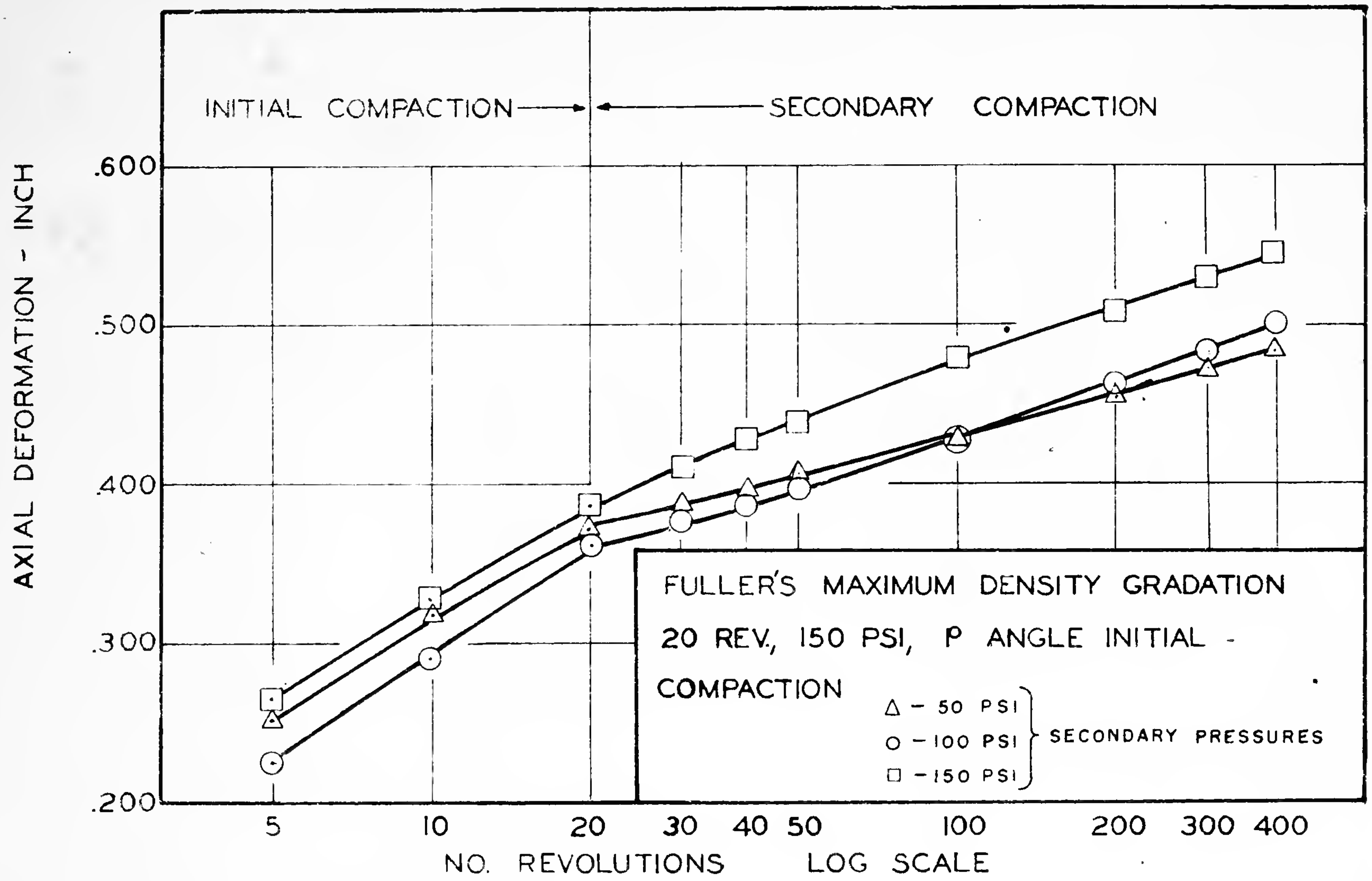

FIG. 7 AXIAL DEFORMATION VS NO. REVOLUTIONS

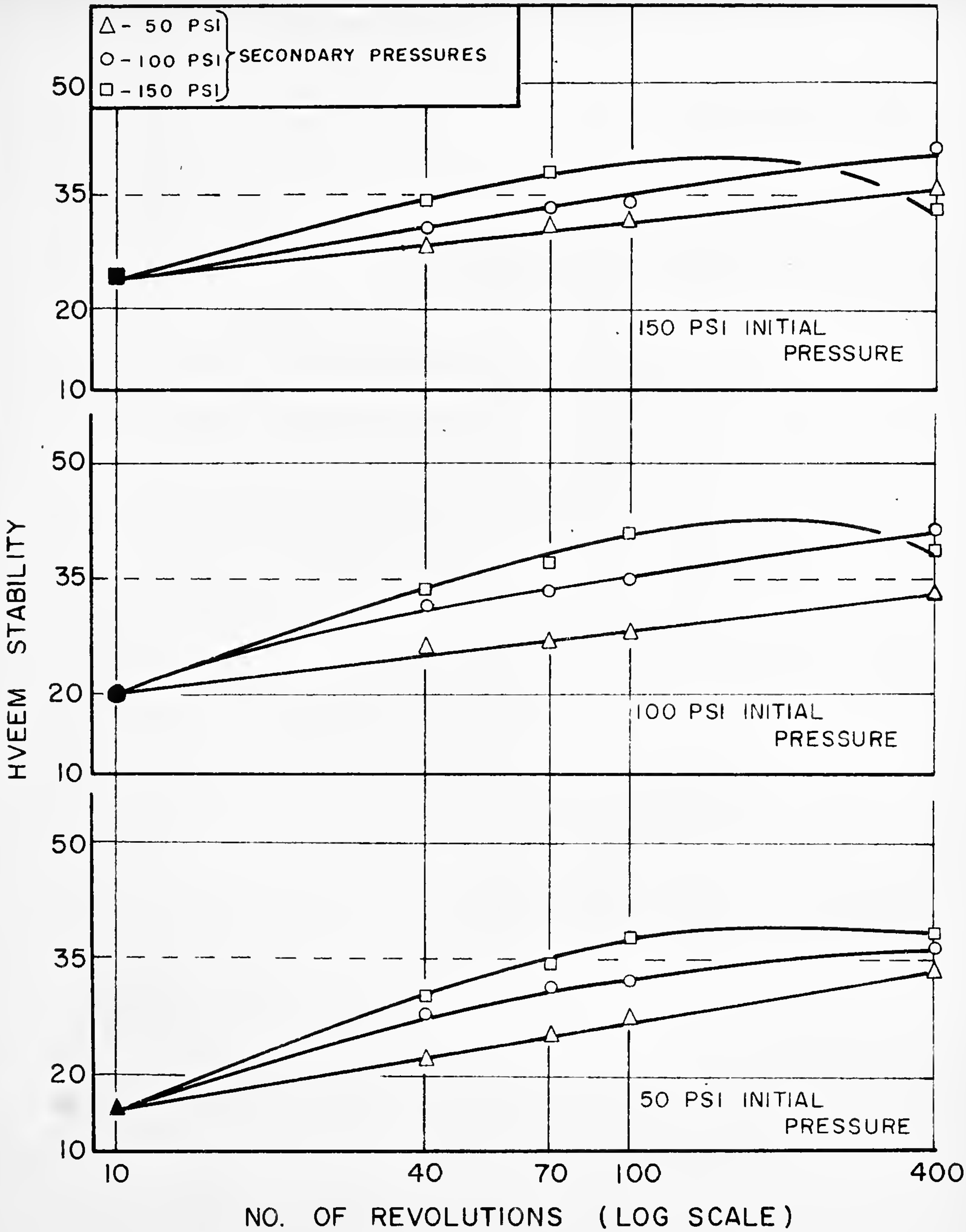

FIG. 8 HVEEM STABILITY VS NO. OF REVOLUTIONS

10 REVOLUTION INITIAL COMPACTION, FULLER'S MAXIMUM DENSITY GRADATION, 4 % ASPHALT

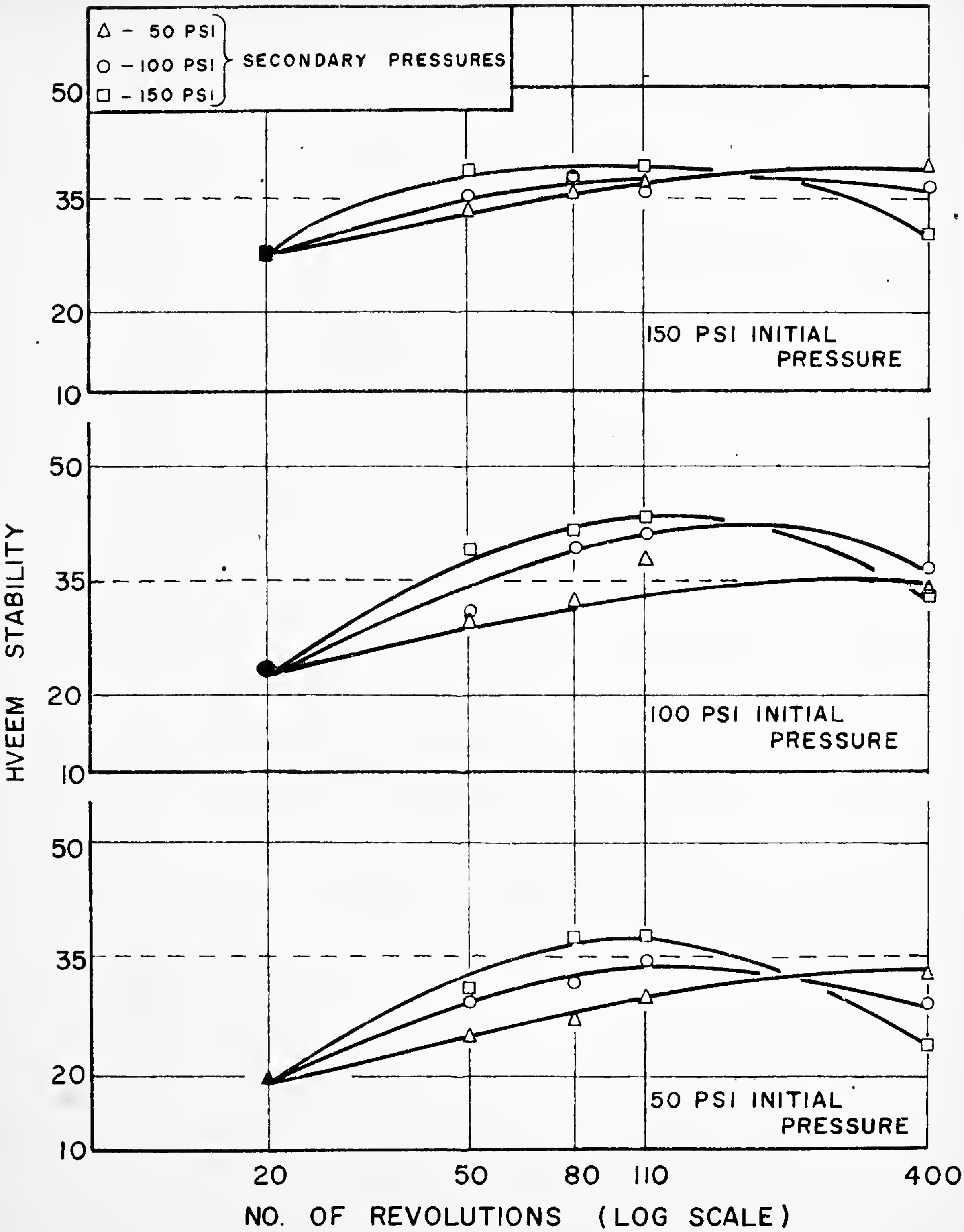

FIG. 9 HVEEM STABILITY VS NO. OF REVOLUTIONS

20 REVOLUTION INITIAL COMPACTION, FULLER'S MAXIMUM DENSITY GRADATION, 4 % ASPHALT

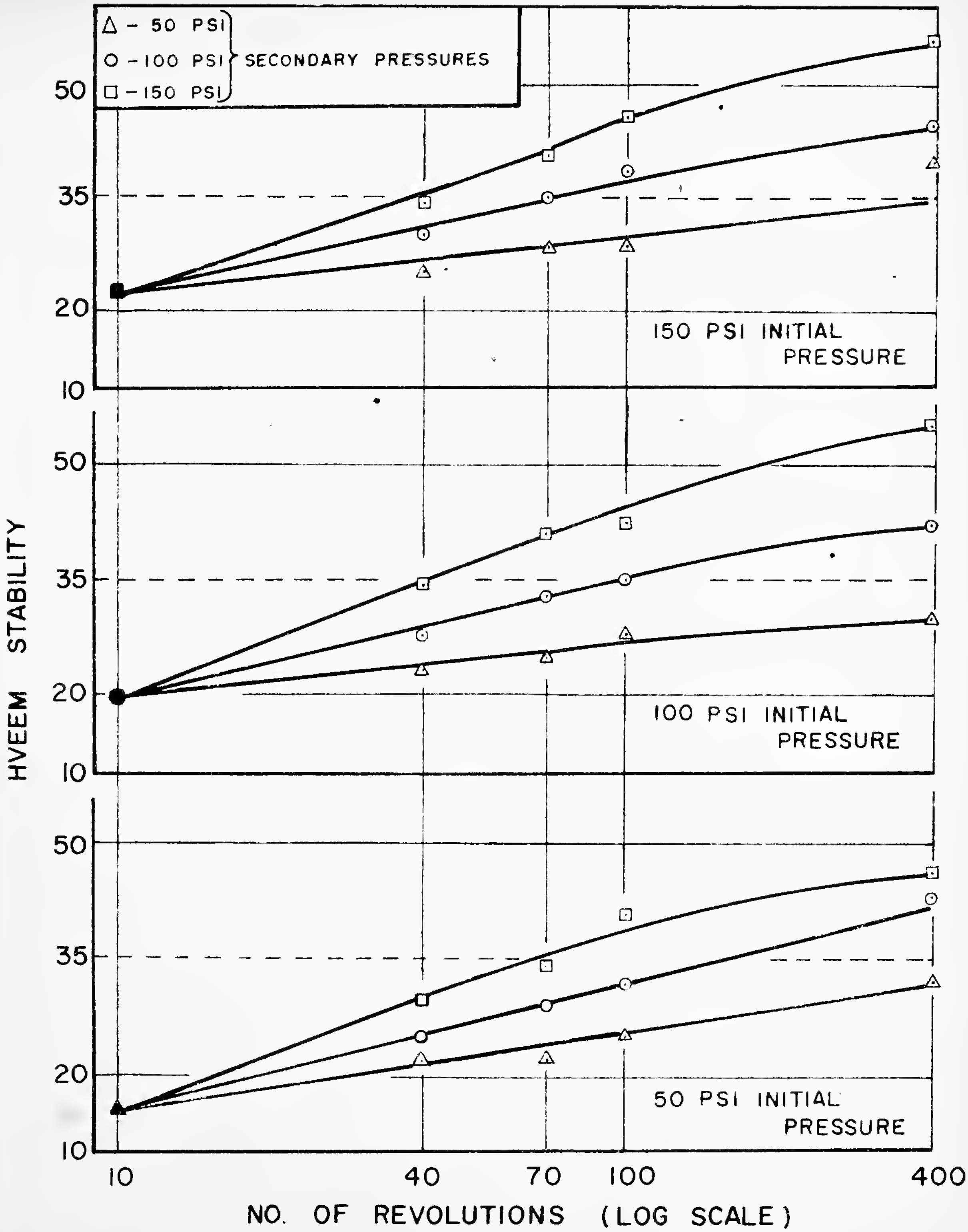

FIG. 10 HVEEM STABILITY VS NO. OF REVOLUTIONS

10 REVOLUTION INITIAL COMPACTION
GRADATION D, 4% ASPHALT

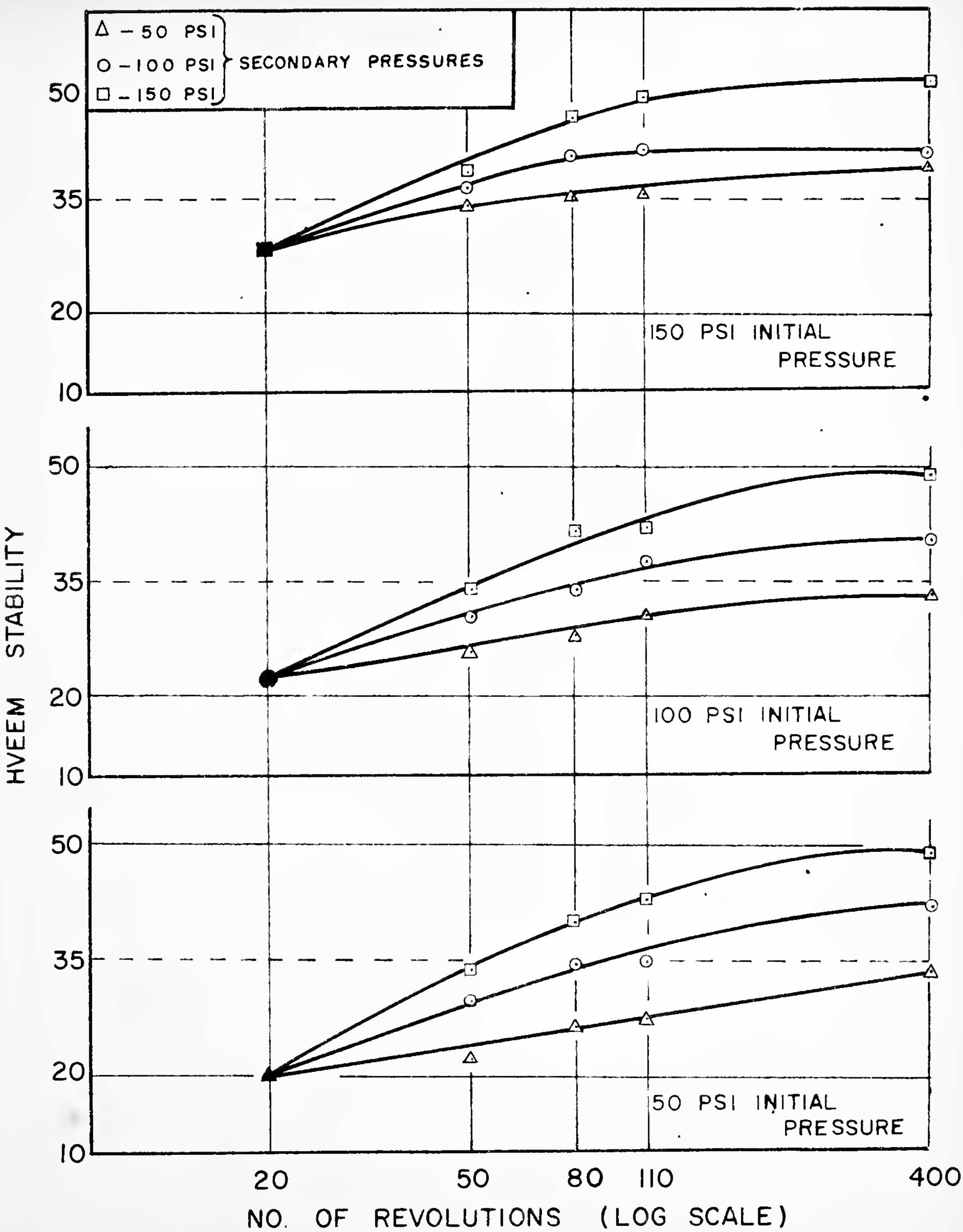

FIG. 11 HVEEM STABILITY VS NO. OF REVOLUTIONS

20 REVOLUTION INITIAL COMPACTION
GRADATION D, 4 % ASPHALT

stability determined experimentally from the average of three stability measurements for each initial pressure - 50, 100, and 150 psi. Other symbols represent only a single stability determination; however, duplicate determinations were made for those cases where a stability decrease occurred with additional revolutions. It will be noted from the figures that the graphs approximate straight lines for low pressures up to approximately 100 revolutions. For up to 100 revolutions the stability vs revolutions relationship would be parabolic on an arithmetic plot.

Gradation

For gradation D (Figures 10 and 11) increasing revolutions increased stability for the entire range of revolutions. This was not the case for the Fuller gradation shown in Figures 8 and 9. Stabilities for the high secondary pressures decreased with increasing secondary revolutions, indicating that this measurement may provide a relative index of mixture resistance to loss of stability under traffic. For the Fuller gradation, shown in Figures 8 and 9, decreases in stability may be noted at the 400 revolution level for both 10 and 20 revolution initial compaction. In general, greater decreases in stability occurred in specimens compacted using higher secondary compaction pressures. This result should be expected from energy considerations, i.e., because compaction is an energy-consuming process the results of compaction should be measurable in energy units.

Stability values for the Fuller gradation generally increased up to 100 revolutions. At 400 revolutions marked decreases in stability were observed for both 10 and 20 revolution initial compaction. Specimens compacted initially for 20 revolutions had somewhat lower stability values after 400 revolutions in most cases than specimens compacted initially for 10 revolutions. Because the only difference between the 10 and 20 revolution initial compaction was the amount of compaction that occurred at the initial compaction temperature (225F), it was concluded that the difference in compaction temperature was responsible for the apparent differences in stability and in resistance to loss in stability. No detailed attempt was made in this study to analyze the effects of compaction temperature on specimen stability; however, the stability difference observed indicates some type of compaction temperature specification to be necessary to insure uniformity of compaction. It is recognized that asphalt in thin films exhibits a greater resistance to compaction at low temperatures than it does at high temperatures. For the Fuller gradation, increased initial compaction decreased the secondary compaction that could be applied before loss in stability occurred.

Design Procedures

The preceding tests were performed to study the manner in which stability values were influenced by compaction variables thought to be somewhat representative of those occurring in bituminous pavements under traffic. To obtain a comparison of selected laboratory design

test characteristics for gyratory- and kneading-compacted specimens, additional tests were performed.

Design of Dense-Graded Mixes

Figure 12 presents a semilog plot of percent voids vs secondary number of revolutions for 20 revolutions initial compaction of the Fuller gradation mixture with four percent asphalt. Comparison of Figure 12 with Figure 9 shows that when degree of compaction of this mixture is such that the void content is less than two percent, additional compaction will result in a decrease in stability. A good correspondence between percent voids values decreasing to less than two percent and widening of the gyrographs was also indicated. Some typical gyrographs are presented in Figure 13.

To relate the gyratory design technique to a standard design procedure, six specimens of the Fuller gradation were prepared by the standard kneading compaction technique specified in the Hveem design procedure. Figure 14 presents a plot of Hveem stability and percent voids vs percent asphalt. This graph indicates that four percent asphalt is the maximum asphalt content that this mixture can accommodate and remain stable under the compactive effort applied. The rather steep slope of the stability vs asphalt content curve indicates that the mix is quite sensitive with respect to amount of asphalt and infers mixture sensitivity with increased compaction. Figures 8 and 9 also indicate that four percent asphalt is the maximum asphalt content that may be accommodated by a stable mixture of this gradation under the compactive effort indicated in these Figures.

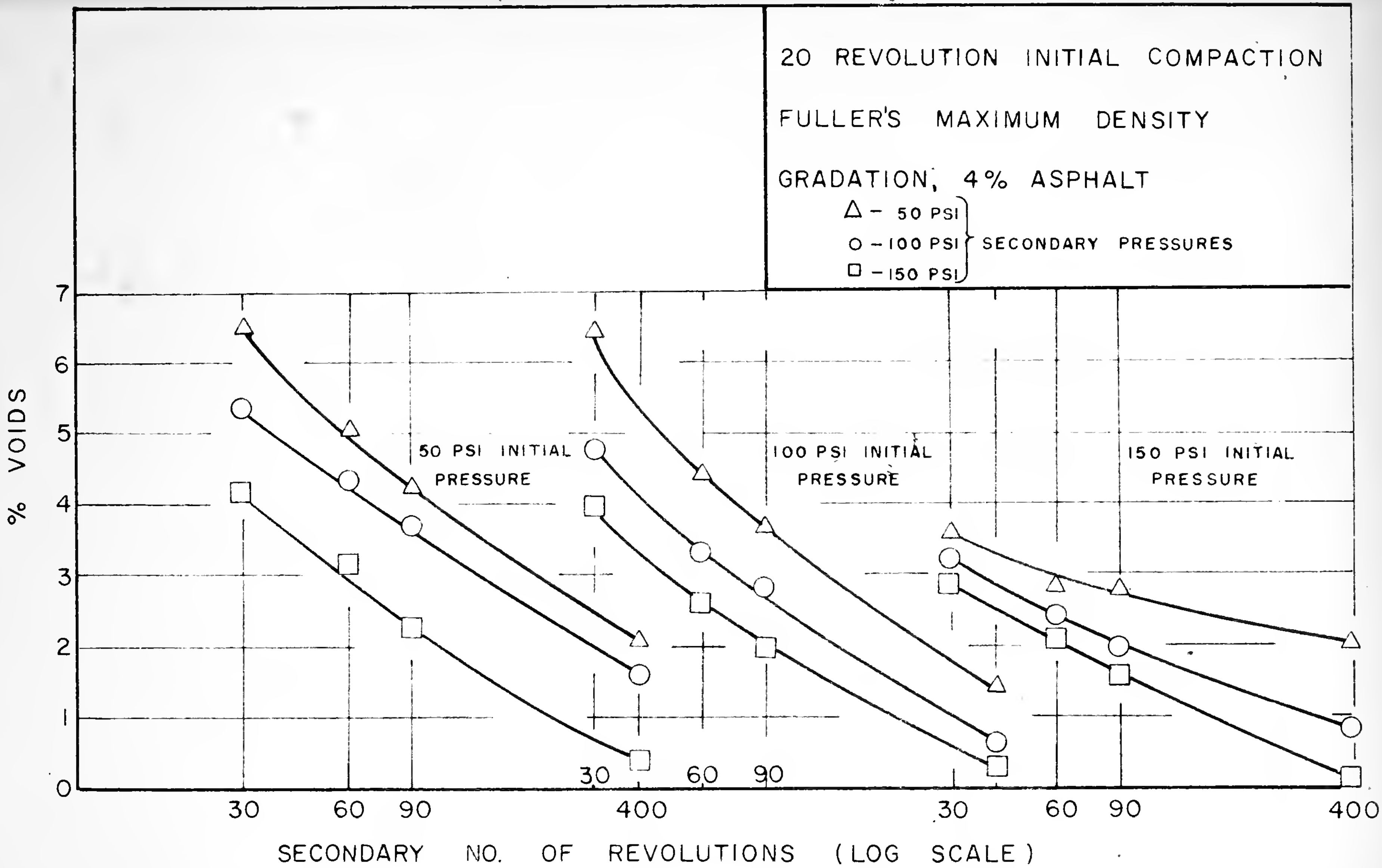

FIG. 12 % VOIDS VS NO. OF REVOLUTIONS

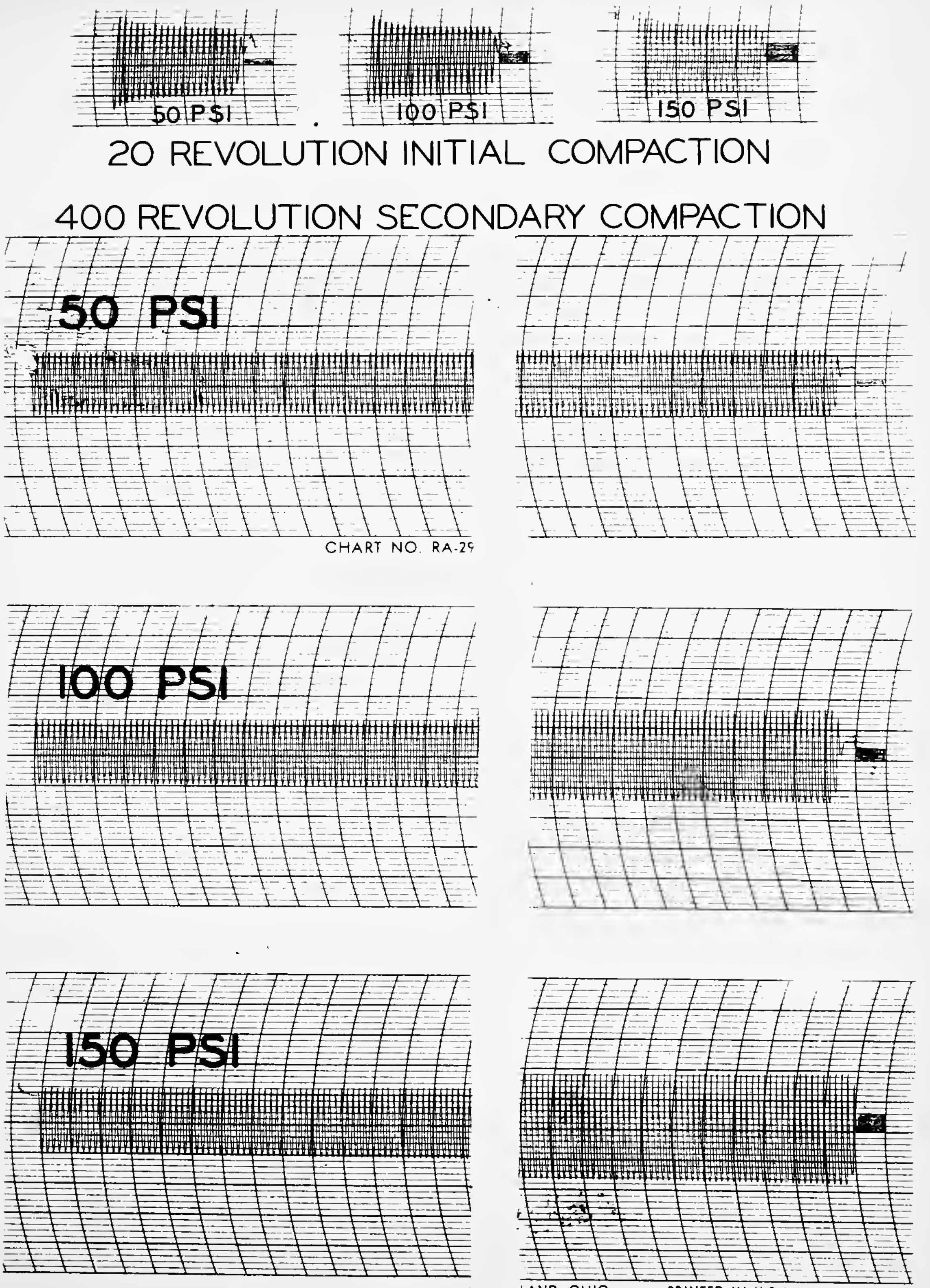

FIG. 13 TYPICAL GYROGRAPHS-FIXED ROLLER OPERATION

FULLER'S MAXIMUM DENSITY GRADATION

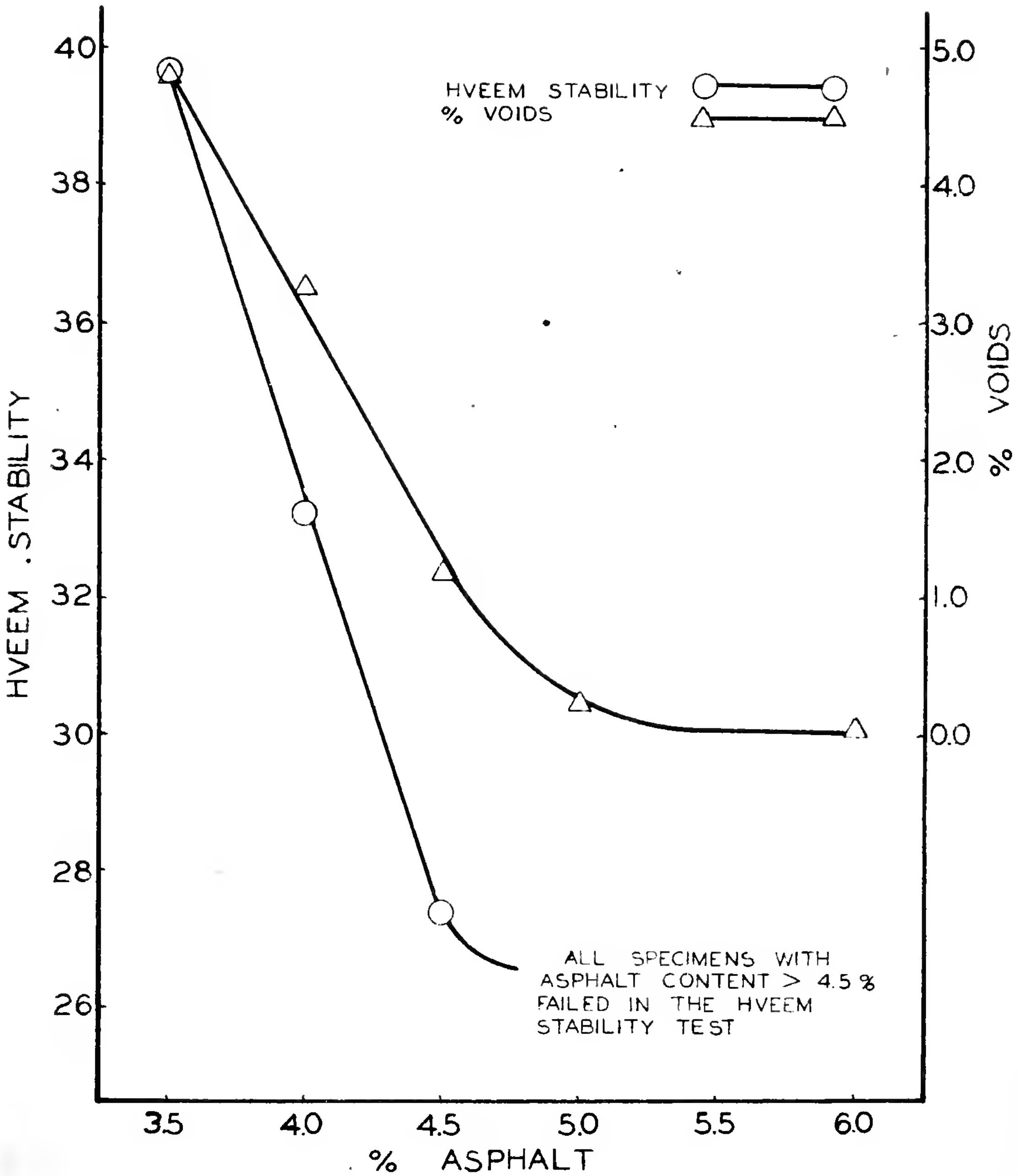

FIG. 14 HVEEM STABILITY AND % VOIDS VS % ASPHALT

FULLER'S MAXIMUM DENSITY GRADATION, KNEADING COMPACTION

From this it was concluded that a design procedure utilizing the widening gyrograph concept was adequate for specifying asphalt content of dense-graded mixes.

Design of Open-Graded Mixes

To study the possibility of using the gyratory testing machine to select an optimum asphalt content for open-graded mixes, 60 gradation D specimens varying in asphalt content from four to seven percent were compacted in the gyratory testing machine and tested in the Hveem stabilometer. Figure 15 shows sampling plots of Hveem stability vs number of revolutions for these specimens. In each case stability values increased with increased number of revolutions. However, stability at 400 revolutions decreased with increasing asphalt content for 100 psi ground contact pressure. For all 60 specimens there was no widening of the gyrographs with increasing numbers of revolutions up to the 400 revolutions applied.

Comparison of the results presented above with results from the standard Hveem procedure was also made. Four specimens were compacted using the standard Hveem compaction procedure. Figure 16 is a plot of Hveem stability and percent voids vs percent asphalt which can be compared to Figure 14 which contains results obtained for the dense mix. It will be noted that stability values for kneading-compacted specimens shown in Figure 16 are much lower than the maximum stability values shown in Figure 15 for mixtures of the same composition compacted by gyratory compaction. No indication of a critical asphalt content was evident from either stabilometer values or widening gyrographs for specimens of gradation D compacted by gyratory compaction up to 400 revolutions.

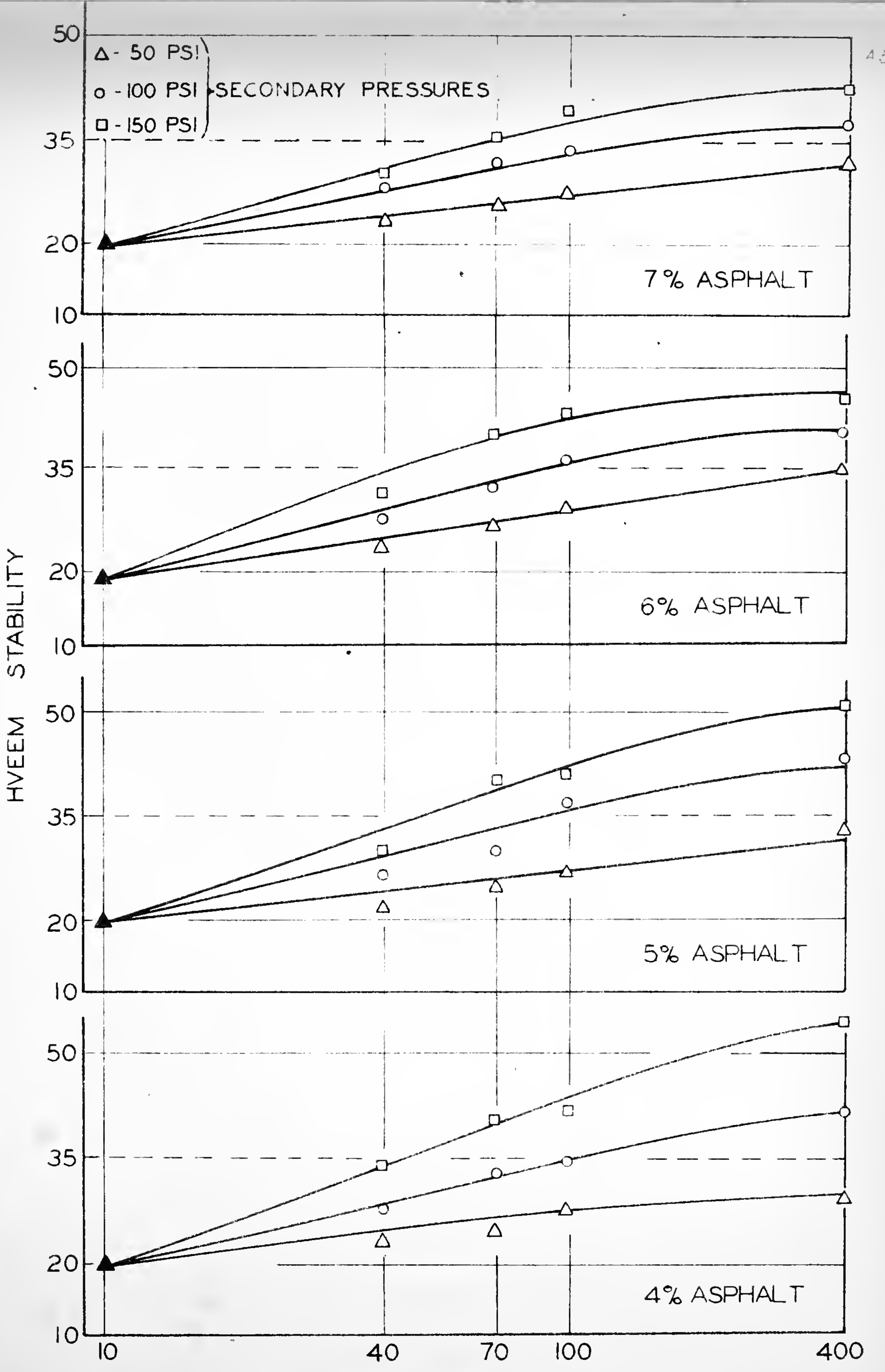

FIG. 15 HVEEM STABILITY VS NO. OF REVOLUTIONS
10 REVOLUTION, 100 PSI INITIAL COMPACTION
GRADATION D, VARYING ASPHALT CONTENT

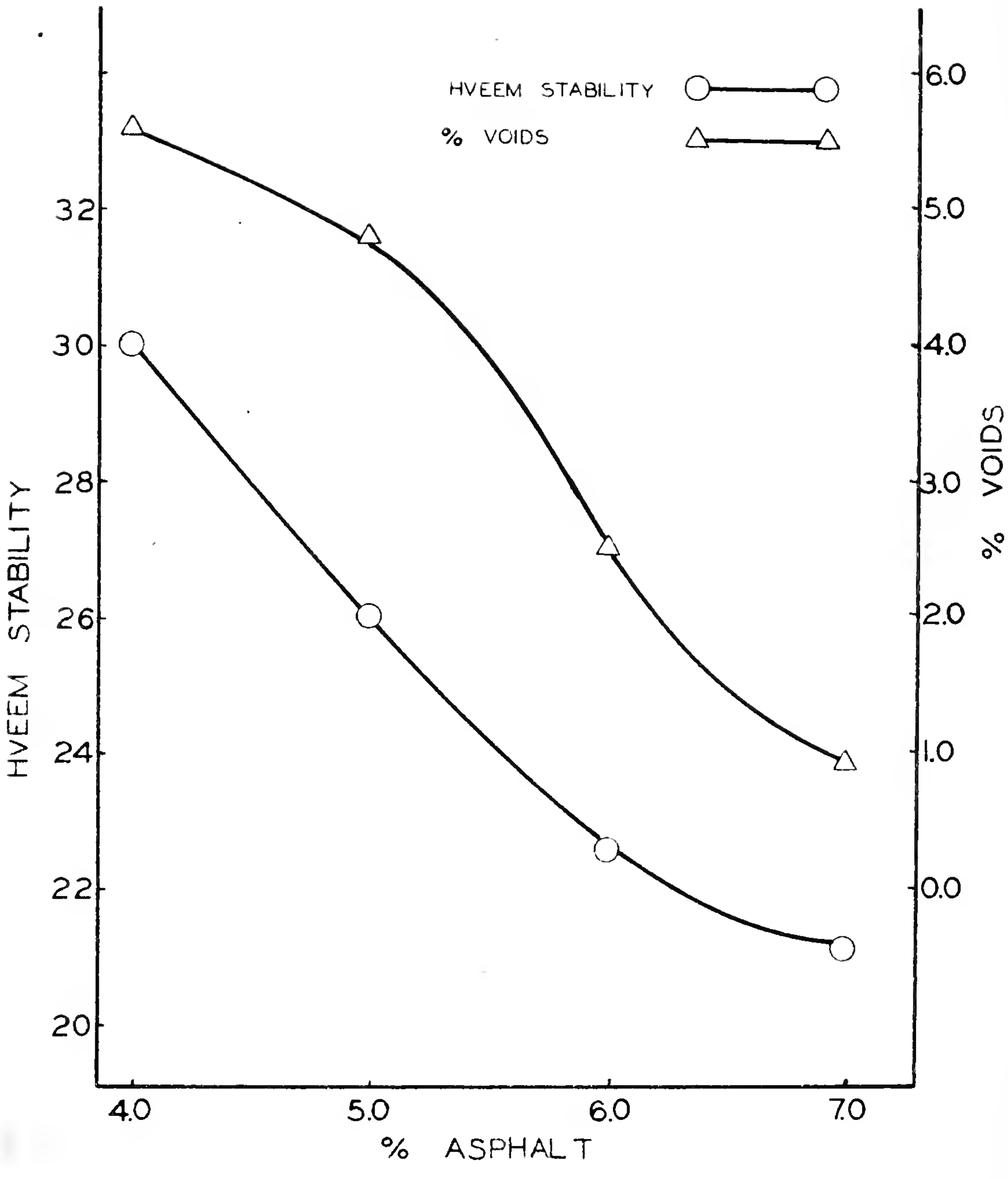

FIG. 16 HVEEM STABILITY AND % VOIDS VS % ASPHALT

GRADATION D, KNEADING COMPACTION

Figure 16 shows that an asphalt content of [illegible] percent is required for gradation D to obtain the four percent voids generally desired in the Hveem design procedure. [illegible] shows that this mixture would not be stable according to the Hveem criteria because 5.5 percent asphalt [illegible] yield a stability of only 2[illegible] less than that required for light traffic. Values of percent voids in Table 9 for gradation D gyratory-compacted specimens [illegible] percent asphalt were 3.7, [illegible], and 2[illegible] percent, respectively, for secondary pressures of [illegible], [illegible], and [illegible] psi and [illegible] revolutions. From the top graph of Figure [illegible] it is seen that this compactive effort yields stabilities of 35 to [illegible]. For this same range of percent voids (2.4 to [illegible] percent), [illegible] stabilities for kneading compaction to be less than [illegible] units. Thus, for the same percent voids, stabilities for kneading-compacted specimens and gyratory-compacted specimens of gradation D are [illegible].

Variation of [illegible]

By way of possible explanation for the differences in results obtained by kneading and gyratory compaction of the most open gradation it should be noted that the high kneading foot pressures specified by the Hveem design kneading compaction procedure produced considerable degradation in specimen tops. Although the percent voids in specimens compacted by the two machines might be equal, this could represent an average of a low-void mix in the top and a high-void mix in the bottom of the kneading-compacted specimens.

Busching and Goetz

To support [illegible]

[illegible]

testing [illegible]

[illegible]

It was found that [illegible] on the average, [illegible] test are shown in Table 12.

[illegible]

Gradation [illegible]
10 [illegible]
[illegible]

[illegible]

Bussing and Costs

Unit Weight [illegible]

Gradation D
10 Revolutions, 50 [illegible]
4% Asphalt Cement

Seconds [illegible]
Air-Fill [illegible]

[illegible]

[illegible]

10

100

Busching and Goetz

For kneading-compacted specimens [illegible] height [illegible] studied by comparing [illegible] gradation I specimens [illegible] compaction using the [illegible] Asphalt [illegible] percent [illegible] for these [illegible] [illegible] was observed.

[illegible]

[illegible]

[illegible] studied by placing [illegible] pieces [illegible] their long axes vertical in a plastic [illegible] mold. These samples were then compacted [illegible] revolutions using the fixed [illegible] upper roller [illegible] gyratory

Table 13

Unit Weight Gradient of Kneading-Compacted Specimens

Gradation D

Asphalt Content, %	Bulk Unit Weight - Pcf Top	Bulk Unit Weight - Pcf Bottom	Bulk Unit Weight - Pcf Top-Bottom
4	146.0	138.5	7.5
4½	147.3	142.9	4.4
5	148.5	142.3	6.2
5½	148.2	142.3	5.9
6	151.0	142.9	8.1
6½	148.5	144.8	3.7

testing machine. Particle reorientation can be seen from the photographs shown in Figure 17 and 18. The photographs show that the gyratory compaction reoriented the aggregate particles into positions where their long axes lie horizontal. It should be noted that the aggregate forms concentric circles in the reoriented position. It is recognized that the opportunity for reorientation would be greater in a plastic clay than in an aggregate mix where there is either particle to particle contact or particle separation by thin plastic films. Within the limits imposed by the above conditions and the confinement of the compaction mold, particle orientation qualitatively similar to that which occurs under traffic appears possible using the gyratory shear method of compaction.

LONG SLENDER AGGREGATE

400 REVOLUTIONS
50 PSI RAM PRESSURE
1° ANGLE OF GYRATION

FIG. 17 STUDY OF PARTICLE ORIENTATION

1200 REVOLUTIONS	5400 REVOLUTIONS
40 PSI RAM PRESSURE	25 PSI RAM PRESSURE
1° ANGLE OF GYRATION	1° ANGLE OF GYRATION

FIG. 18 STUDY OF PARTICLE ORIENTATION

Summary of Results and Conclusions

The following results and conclusions appear to be justified by the experimental data collected. It should be noted that these results and conclusions are applicable to the materials and testing procedures of this specific research only and may not be extended beyond these limits without appropriate correlation.

1. For the specimens of the Fuller gradation with four percent asphalt subjected only to simulated construction compaction in the gyratory testing machine and tested in the Hveem stabilometer, a significant increase in bulk unit weight was effected by the compression imposed upon the specimens during testing in the stabilometer. The average increase in bulk unit weight was 1.67 pcf.

2. Analysis of variance for the five main factors studied in the laboratory showed all factors were statistically significant in affecting specimen compaction as evaluated by change in stability. Factors in order of importance were: secondary revolutions, initial pressure, secondary pressure, initial revolutions, and gradation. Data from controlled field studies would be necessary to determine whether a realistic simulation of the pavement condition is effected by this laboratory procedure. However, the same statistical methods could be applied to a field study for an evaluation of field compaction and stability variables.

3. In all cases studied, including both the dense and open gradations at all asphalt contents, increases in initial compaction pressure and number of revolutions increased the initial stability. Increased initial

compaction decreased the secondary compaction that could be applied before loss in stability occurred.

4. Axial deformation of specimens under simulated traffic was greater for specimens initially compacted at high pressures. No decrease in unit weight occurred during compaction; confinement in the compaction mold was sufficient to prevent this.

5. Good correlation was obtained between widening of the gyrograph and loss in Hveem stability for the mixture employing the Fuller gradation. Stability values for kneading- and gyratory-compacted specimens compared favorably for the same values of percent voids. Hence it is indicated that for this laboratory study good stability and voids correlations were obtained for the dense mix compacted by the kneading compactor and the gyratory testing machine.

6. For Gradation D, stability values of kneading-compacted specimens were lower than the stability values of gyratory-compacted specimens for specimens having the same percent voids. High stability values were measured for gradation D specimens containing from four to seven percent asphalt and compacted to 400 revolutions. No indication of loss of stability was observed from the widening of the gyrographs. Kneading-compacted specimens of the same open-type gradation had stability values of 30 or less for the four to seven percent range of asphalt content studied. It was concluded that for gyratory- and kneading-compacted specimens marked differences in stability were attributable to differences in the type of compaction imposed on the specimens. A thorough study of the factors responsible for this discrepancy with respect to the gradation D mixture was not undertaken.

7. Gradation D specimens containing four percent asphalt that were compacted in the gyratory testing machine had variation in unit weight from top to bottom that differed with amount of compaction. Unit weights of specimen bottoms tended to be slightly greater than the unit weights of specimen tops.

8. For gradation D specimens with varying asphalt content, kneading compaction as specified in the Hveem design procedure produced specimens whose unit increased markedly from bottom to top.

9. Stability values for specimens compacted by the gyratory machine were found to be a function of temperature and mixture composition. Both mixture gradation and asphalt content were factors of composition that influenced stability values.

10. Compaction of a plastic clay containing hand-placed pieces of slender aggregate showed that gyratory compaction allowed pieces to orient themselves into horizontal position. Orientation of these aggregate pieces in the plastic clay media produced a pattern of concentric circles.

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